PUZZLES IN ASTROPHYSICS IN THE PAST AND PRESENT [a]

V. Berezinsky
INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ) 67010 Italy
and Institute for Nuclear Research, Moscow
E-mail: berezinsky@lngs.infn.it

ABSTRACT

About 400 years have passed since the great discoveries by Galilei, Kepler and Newton, but astronomy still remains an important source of discoveries in physics. They start with puzzles, with phenomena difficult to explain, and which in fact need for explanation the new physics. Are such puzzles existing now? There are at least three candidates: absence of absorption of TeV gamma radiation in extragalactic space (violation of Lorentz invariance?), absence of GZK cutoff in the spectrum of Ultra High Energy Cosmic Rays (new particle physics?), tremendous energy (up to 10^{54} ergs) released in Gamma Ray Bursts during a time scale of a second (collapsing stars or sources of a new type?). Do these puzzles really exist? A critical review of these phenomena is given.

1. Introduction

ALL GREAT DISCOVERIES IN ASTROPHYSICS
APPEARED UNPREDICTABLY; WHAT WAS PREDICTED
WAS NOT DISCOVERED.

Not many good things fall down on us from the sky, but discoveries do. I will list below a short list of astrophysical discoveries of the last four decades, separating intuitively astrophysics from cosmology.

Quasars were discovered in early 1960s as compact radio sources. Mathews and Sandage in 1960 identified radio source 3C48 with a stellar-like object. Schmidt in 1963 deciphered the optical spectrum of quasar 3C273 assuming its redshift, $z = 0.158$. Surmounting resistance of sceptics, this explanation moved the source to the distance of 630 Mpc and made its luminosity uncomfortably large, $L \sim 10^{46}$ erg/s. This puzzling energy release resulted in the long run in the discovery of a *black hole*, an object of general relativity.

Pulsars were discovered first in 1967 by a student of A. Hewish, Jocelyn Bell. She observed a puzzling periodicity of radiopulses from an unknown source. After short but intense discussion of different possible sources, including extraterrestrial civilisations and "little green men", the magnetised rotating neutron stars, the pulsars, were found to be responsible. It opened a new field of cosmic physics: *relativistic*

[a] I dedicate this talk to D.V.Sciama, great personality and outstanding physicist

electrodynamics.

The atmospheric neutrino anomaly and the solar neutrino problem went along most difficult road to the status of discovery. The puzzling phenomenon in both cases was a neutrino deficit as compared with calculations. But scepticism of the community, especially in the case of the solar neutrino problem was strong. Pushed mostly by Davis and Bahcall, the solar neutrino problem moved like a slow coach along a road two decades long. Fortunately, physics differs from democracy: opinion of majority means usually less than that of ONE. These two obscure puzzles have turned (or have almost turned) into discovery of the most fascinating phenomenon, *neutrino oscillations.*

Supernova SN 1987a became elementary-particle laboratory in the sky for a study of properties of neutrinos, axions, majorons *etc.* Detection of neutrinos [1] became a triumph of the theory: the number of detected neutrinos, duration of the neutrino pulse and estimated neutrino luminosity have appeared in agreement with theoretical prediction. Gravitational collapse as a phenomenon providing the SN explosion was confirmed.

However, some puzzles remain. Presupernova was the blue supergiant, not the red one as a theory of stellar evolution prescribes. But what is more puzzling is rotation. The asymmetric ring around SN 1987a implies that the presupernova was a rotating star (it would be a surprise if not!). But the striking agreement of neutrino observations with calculations were obtained for a non-rotating presupernova. Inclusion of rotation in calculations is a very difficult task. The simplified calculations [2] demonstrate that rotation changes predictions dramatically: temperature of neutrinosphere diminishes by factor 2, total energy of emitted neutrinos becomes 6 times less and the number of detected neutrinos should be an order of magnitude less.

1.1 Greatness of false discoveries

WHEN FIRST APPEARED THE PUZZLES LOOK WEAK.
SAVE YOUR TIME AND SAY: IT'S RUBBISH.
IN 90% OF CASES YOU WILL BE RIGHT.

False discoveries often have greater impact on physics than the true ones.

In the end of 60s and the beginning of 70s using long baseline interferometry, it was found that gas clouds in quasars and radiogalaxies in some cases had velocities exceeding the light speed by factor 4 - 10. In fact the measured velocity was a projection of velocity on the plane perpendicular to the line of view. Accurately written in relativistic mechanics, this (apparent) velocity is

$$v_{app} = \frac{v \sin\theta}{1 - \frac{v}{c}\cos\theta}. \qquad (1)$$

Provided by ultrarelativistic velocity of an object $v \sim c$, the apparent velocity can exceed speed of light. *Astrophysics of relativistic objects*, now a subject of university courses, was born.

Cyg X-3 saga is a story of a different kind.

Cyg X-3 is a galactic binary system well studied in all types of radiations, most notably in X-rays. In 80s many EAS arrays detected from it 4.8 hour periodic "gamma-ray" signal in VHE (Very High Energy, $E \geq 1$ TeV) and UHE (Ultra High Energy, $E \geq 0.1 - 1$ PeV) ranges. The list of these arrays included Kiel, Haverah Park, Fly's Eye, Akeno, Carpet-Baksan, Tien-Shan, Platey Rosa, Durham, Ooty, Ohya, Gulmarg, Crimea, Dugway, Whipple and others. Probably it is easy to say that there was no single EAS array which claimed no-signal observation. Additionally, some underground detectors (NUSEX, Soudan, MUTRON) marginally observed high energy muon signal from the direction of this source. Apart from the Kiel array, which claimed 6σ signal, the confidence level of detection was not high: $3 - 4\sigma$.

In 1990 - 1991 two new generation detectors, CASA-MIA and SYGNUS, put the stringent upper limit to the signal from Cyg X-3, which excluded early observations.

Apart from two lessons:

(i) good detectors are better than bad ones,

(ii) "3σ" discoveries should not be trusted, even if many detectors confirm them,

experience of Cyg X-3 has taught us how to evaluate statistical significance searching for periodic signals.

The false discovery of high energy radiation from Cyg X-3 had great impact on theoretical high energy astrophysics, stimulating study of acceleration in binary systems, production of high energy gamma and neutrino radiation and creation of high energy astrophysics with new particles, such as light neutralinos, gluinos *etc.*

2. Violation of Lorentz Invariance

Violation of Lorentz invariance (LI) is often suspected in astrophysics because of large Lorentz factors being sometimes involved. Before describing these suspicions, we will discuss the aesthetic side of the problem: is there an aesthetically attractive theory with a broken LI?

Breaking of LI, even extremely weakly, leads to existence of the absolute Lorentz frame. This is a qualitative difference between the two theories. Absence of continuous transition from one theory to another looks disturbing.

Lorentz invariance is a basic principle for building a Lagrangian for any interaction. How is it possible to abandon it?

All questions raised above disappear in spontaneously broken LI. Equations of motion remain Lorentz invariant. The violation occurs spontaneously in the solutions. Lagrangians for all interactions are constructed as Lorentz scalars and spontaneous LI breaking occurs due to non-zero values of field components in vacuum states.

Breaking of LI can be made arbitrarily small, and all physical effects accompanied by LI breaking are small too. The absolute Lorentz frame exists, but all physical effects, which distinguish it from other frames, are small, and thus all frames are nearly equivalent, similar to Lorentz invariant theory.

2.1 Spontaneously broken Lorentz invariance

The Lorentz invariance is spontaneously broken when time component of vector or tensor field obtains non-zero value. The necessary condition for the phase transition to such configuration is existence of potential minimum at this value. Such a condition can be fulfilled only in some exceptional cases, e.g in superstring theories [3] and in some specific D-brane models with extra dimensions [4,5]. The interactions responsible for such potential minimum usually do not appear in conventional four-dimensional renormalizable theories.

Consider for example the Lorentz invariant interaction of superheavy tensor field $T_{\mu\nu...}$ with ordinary field described by spinor ψ. If, for example, string interactions set non-zero vev for time components of this tensor field, the considered interaction term is reduced to the term which explicitly breaks LI [6]:

$$\mathcal{L}_{int} = \frac{\epsilon}{M^k} v_k \bar{\psi} \Gamma (i\partial_0)^k \psi, \tag{2}$$

where $v_k =< T_{00...} >$ is vev, Γ is build from γ's , ϵ is dimensionless constant, and M is a superstring mass scale. Such LI breaking term modifies dispersion relation for a particle ψ and results in astrophysical consequences [7].

We shall give here a simple example of spontaneous LI breaking accompanied by modification of dispersion relation for an ordinary particle.

Let us consider the Lagrangian for an ordinary spinor particle

$$\mathcal{L} = i\bar{\psi}\gamma_\mu \partial_\mu \psi - m\bar{\psi}\psi + \mathcal{L}_{int}, \tag{3}$$

where interaction with superheavy field $T_{\mu\nu}$ is described by

$$\mathcal{L}_{int} = \frac{\epsilon}{M^2} T_{\mu\nu} \bar{\psi}\gamma_\mu \partial_\nu \psi. \tag{4}$$

After spontaneous symmetry breaking $< T_{00} >= v^2$ the associate Klein-Gordon equation [8] for a non-interacting particle can be readily obtained as

$$(\partial_\mu^2 + m^2 - \frac{\epsilon}{M^2} v^2 E^2)\psi = 0 \tag{5}$$

The corresponding dispersion relation is

$$p_\mu^2 - m^2 + \frac{\epsilon}{M^2} v^2 E^2 = 0. \tag{6}$$

2.2 Modified dispersion relations and threshold of reactions

In astrophysical applications one often considers a collision of very high energy particle

with low energy particle from background radiation. This is the case of absorption of TeV gamma-radiation on infrared photons and so-called GZK[9)] cutoff, when very high energy proton collides with a microwave photon, producing the pion. A threshold of such reactions is determined by momentum of a particle in c-m system, which has very large Lorentz factor in laboratory system. At large Lorentz factors, *i.e.* at large energy of one of colliding particles in laboratory system, the dispersion relation is modified and affects the threshold of reaction in laboratory system.

Let us consider this effect in $\gamma + \gamma \to e^+ + e^-$ collision when one photon has large energy E_γ and another - small energy ϵ_γ. The conservation of energy and momentum requires

$$(k_\mu + k'_\mu)^2 = (p_\mu + p'_\mu)^2, \tag{7}$$

where k_μ and p_μ are 4-momenta of photon and electron, respectively, and their 4-momenta after collision are shown by primes. In LI case $k_\mu^2 = k'^2_\mu = 0$ and $p_\mu^2 = p'^2_\mu = m_e^2$, and energy-momentum conservation requires

$$\sqrt{E_\gamma \epsilon_\gamma} > m_e \tag{8}$$

as the threshold condition. In the case of modified dispersion relation $p_\mu^2 = E_e^2 - \vec{p}_e^{\,2} \approx m_e^2 + \epsilon v^2 E^2/M^2$, as in Eq.(6), and the threshold shifts towards higher energies in laboratory system.

2.3 Astrophysical tests of special relativity

GZK cutoff involves Lorentz transformations with Lorentz factor $\Gamma \sim m_\pi/\epsilon_\gamma \sim 10^{11}$, where m_π is a pion mass and $\epsilon_\gamma \sim 10^{-3}$ eV is a typical energy of microwave photon participating in the photopion reaction. It gives the largest Lorentz factor presently known, up to which LI can be tested. Such a test and proposal to explain the absence of GZK cutoff in experimental data were first suggested by Kirzhnitz and Chechin [10)] in 1972 and later in Refs.[7,11,12,13)].

The other similar process is absorption of TeV gamma radiation on IR background photons. It will be considered at some details in the next Section.

There are some other astrophysical processes, where LI can reveal itself:

- Constancy velocity of light [14)]
- Vacuum Cherencov radiation [12)],
- Vacuum Faraday rotation [12)],
- High energy photon decay [12)],

3. TeV Gamma-ray Crisis?

Propagating through the space filled by IR background radiation, TeV photons are absorbed in $\gamma\gamma_{IR} \to e^+ + e^-$ collisions. A photon with energy E_γ is absorbed by

IR photons with wavelengths shorter than

$$\lambda_{IR} \approx \frac{E_\gamma}{4m_e^2} = 1.2\frac{E_\gamma}{1\ \text{TeV}}\ \mu\text{m}. \tag{9}$$

Thus photons with energies 1 - 20 TeV are absorbed on IR background radiation with wavelengths $1\mu\text{m} \leq \lambda_{IR} \leq 20\mu\text{m}$. For this wavelength range there are both direct measurements and detailed calculations.

The DIRBE instrument[15] (Diffuse Infrared Background Experiment) on COBE spacecraft measures IR diffuse radiation in the band from 1.25 to 240 μm. The measured fluxes are shown in Fig.1.

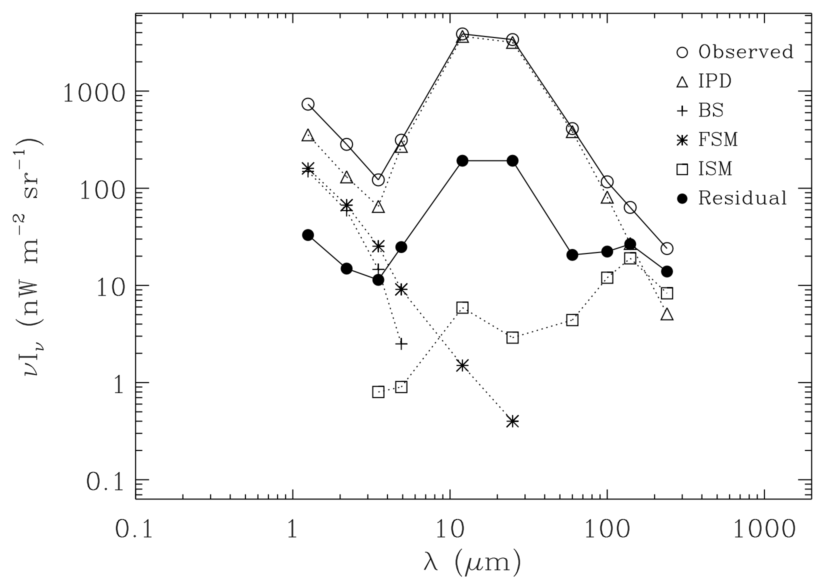

Figure 1: *IR diffuse spectra as measured by DIRBE-COBE in the range 1.25 - 240 μm (from [15]). Extragalactic diffuse flux, shown by filled circles, is obtained by subtraction of contributions due to Interplanetary dust (IPD) shown by triangles, bright galactic sources (BS), shown by crosses, and others.*

Note that the measured flux is very close to that produced by interplanetary dust and after subtraction of this major component the residual is about factor of 20 less.

The data of another COBE instrument, FIRAS (Far Infrared Absolute Spectrometer) in the range 125 - 2000 μm are consistent [16] with DIRBE at overlapping frequencies. An estimate of intergalactic diffuse IR flux from integrating the 15 microns count of IR sources at ISOCAM [17] is also consistent with the DIRBE data. However, a count of sources is always incomplete, and thus the ISOCAM flux at 15 μm can be considered as an lower limit.

Diffuse IR flux was calculated in many works, most notably in two recent works [18,19] (see the references to early calculations there). In Ref.[18] a semi-empirical method is used, while calculations of Ref.[19] are based on galaxy formation models. A feature common to both calculations is bimodal frequency distribution. A peak at about 1 μm is a direct radiation during star formation epoch, and a second peak about 100 μm is due to dust re-radiating the starlight at lower frequencies. It could be (see Fig.2) that observational data confirm this feature. Both calculations give IR flux lower than that of DIRBE.

The results of observations and comparison with calculations are given in Fig.2, taken from Ref. [20].

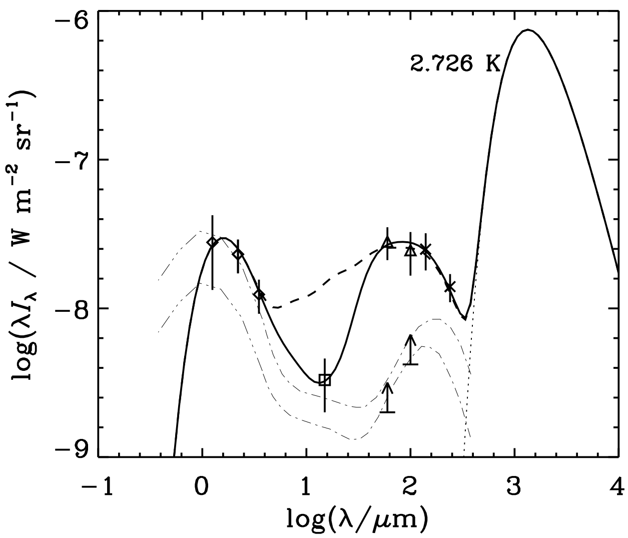

Figure 2: *Intergalactic diffuse IR fluxes* [20]. *The data points are from DIRBE (diamonds), ISOCAM (square) and FIRAS (crosses). These data can be described by a thick solid line or by a solid line with a broken line in the middle. Two theoretical curves (dot-dash ones) have emerged from calculations by Malkan and Stecker* [18].

As was discussed above, the gamma-radiation with energy 1- 10 TeV is absorbed by IR radiation in the range 1 - 10 μm. A gamma-ray source with relevant properties is a nearby blazar Mrk 501. This powerful TeV source is located at suitable distance 155 Mpc (z=0.0336) and its measured spectrum extends from 400 GeV up to 24 TeV without noticeable steepening. However, the expected absorption in the end of the spectrum is appreciable, and to have the observed spectrum without cutoff, the production ("corrected") spectrum must be unnatural, as it is shown in Fig.3 from Ref. [20]. In fact, this unnatural increase in production spectrum corresponds to spectrum cutoff, if the production spectrum is smooth. The cutoff appears when a pathlength diminishes with energy, as it happens when density of target photons increases with wavelength λ. This is the case of dependence of IR flux on λ presented in Fig.2.

If IR flux is taken according to theoretical calculations [18,19], "TeV gamma-ray crisis" disappears. In Fig.4 the observed spectrum Mrk 501 in the flaring state (low

curve) is given together with the production spectrum (upper curve). The absorption in intergalactic space is taken according to IR flux calculated by the authors of Ref.[18] in one of their models. The source spectrum is quite natural with no indication to the "crisis". The similar calculations were made in Ref.[21]. The source (production) spectrum of TeV radiation from Mrk 501 was calculated from the observed spectrum using the theoretical IR flux, according to LCDM model of Ref.[19]. The production spectrum is found to be natural.

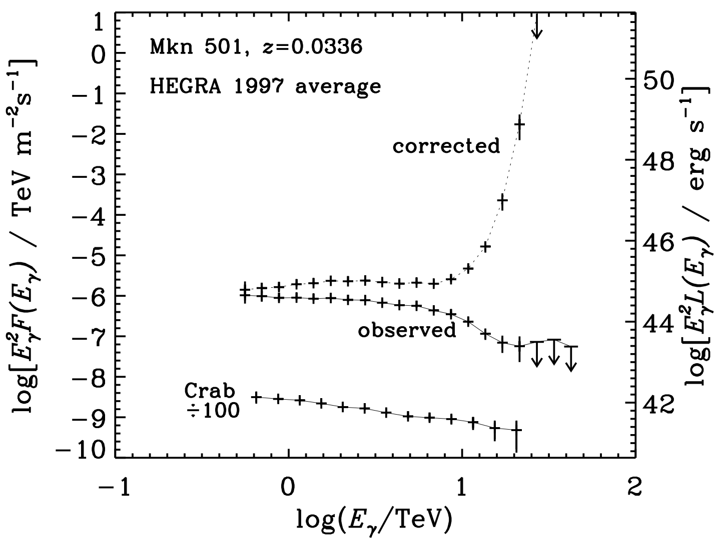

Figure 3: *The production ("corrected") spectrum for Mrk 501 calculated [20] from the observed spectrum and with $\gamma\gamma$ absorption taken into account. Unnaturalness of production spectrum is illustrated by luminosity shown on the right-hand axis.*

In conclusion, "TeV gamma-ray crisis" does not look dramatic. It could be that IR flux measured by DIRBE is slightly overestimated due to incomplete subtraction of galactic or interplanetary components. The frequency dependence of the flux plays crucial role. The spectrum cutoff appears if flux increases with λ sharply enough. If ISOCAM point in Fig.2 is in fact an lower limit, the frequency dependence of IR flux can be smooth (as the broken line shows), and the sharp cutoff is absent.

At present there is no need to involve Lorentz Invariance breaking for solving this problem. A clear test of Lorentz invariance can be done with help of radiation for which the density of target photons and their energy spectrum are reliably known. This case is given by microwave relic radiation. As Fig.2 shows at wavelength $\lambda \sim 300\ \mu$m there is a sharp increase of photon density with λ, which results in the cutoff of gamma-ray spectrum at $E_\gamma \sim 250$ TeV. An absence of such cutoff for a source with known distance to our galaxy (redshift) can be explained only by Lorentz Invariance breaking.

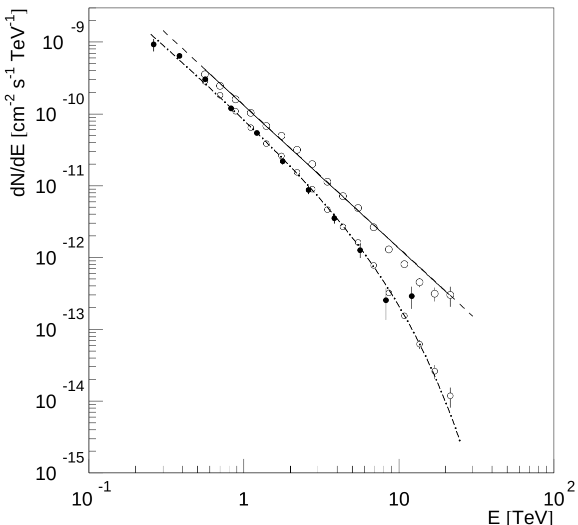

Figure 4: *The observed (low curve) and production (upper curve) spectra of TeV gamma radiation for Mrk 501 (from* [18]*). The production spectrum is calculated using the absorption on IR radiation with the flux calculated in one of the models of Ref.*[18]*.*

4. UHECR: How Serious is the Problem?

The problem with Ultra High Energy Cosmic Rays (UHECR) consists in observation of particles with very high energies, up to $2-3\cdot 10^{20}$ eV, while the ordinary signal carriers such as protons, nuclei, electrons and photons have a small pathlength in intergalactic space. UHE protons loose energy due to production of pions in collisions with microwave photons and their spectra should have a steepening (GZK cutoff [9]) which starts at $E\sim 3\cdot 10^{19}$ eV. UHE nuclei loose energy due to e^+e^- pair production in collisions with microwave photons [22]. Electrons are loosing the energy very fast on microwave radiation. UHE photons are absorbed on extragalactic radio background [23].

UHE particles are observed by Extensive Air Showers (EAS) produced in the atmosphere.

Doubts in existence of UHECR problem are usually expressed in the form of two questions:

- Are energies measured correctly?
- Could the sources of UHECR be located nearby, e.g. in our galaxy or at small distance from it?

I will address below these questions and analyse the status of UHECR problem.

4.1 Energy determination

The energy of a primary particle is determined measuring some characteristics of

EAS (for a review see [24]). The methods are different and agree for determination of UHE energies within $20-30\%$. The error in energy determination is estimated as $15-20\%$ for the good events. The most traditional method of energy measurement is based on the relation between cascade particle density at the distance 600 m from the shower axis and primary energy E. This method (ρ_{600}) was first suggested by Hillas [25], and later confirmed my many Monte Carlo simulations. It was demonstrated that this relation depends weakly on the model of EAS development and on chemical composition of the primaries. The density fluctuations have also minimum at the distance 600 m from the core. For UHE EAS this relation between ρ_{600} and primary energy has been confirmed by calorimetric measurements at Yakutsk for energies up to $4\cdot 10^{18}$ eV. The ρ_{600} method was used in the Haverah Park, Yakutsk and AGASA arrays. In the case of Haverah Park ρ_{600} signal is given by energy release in water Cherenkov detectors.

The Fly's Eye array detects fluorescence light produced by EAS in the atmosphere. The intensity and arrival time of fluorescent radiation to the collecting mirrors allow to reconstruct the longitudinal development of EAS in the atmosphere, and the primary energy is obtained thus practically calorimetrically.

In two cases the primary energy was measured very reliably.

The Fly's Eye detector had an event [26] with very accurately measured longitudinal profile and the primary energy was found to be $E=(3^{+0.36}_{-0.54})\times 10^{20}$ eV. This is the highest energy event.

The AGASA array detected [27] a shower with the core in the dense part of array, Akeno. The lateral distribution of cascade particles, including muons, was measured in the total range of distances from the core up to 3 km. The primary energy is estimated to be in the range $(1.7-2.6)\times 10^{20}$ eV.

The total number of detected showers with energy higher than $1\cdot 10^{20}$ eV is about 20. A sceptic taking event by event could doubt in energy of some of them, but even at most critical analysis several of them survive as cases with energy higher than $1\cdot 10^{20}$ eV. It is already enough to claim existence of the problem.

4.2 What is the GZK cutoff?

The Greisen-Zatsepin-Kuzmin cutoff [9] is caused by interaction of high energy protons with microwave (2.73 K) radiation. At energy $3\cdot 10^{19}$ eV the total energy loss of the proton starts sharply (exponentially) increasing with energy due to pion production $p+\gamma_{2.7K}\to N+\pi$. The exponential character of this increase is caused by the fact that production of pions needs the photons from high energy tail of their distribution, and the number of these photons exponentially increase when proton energy becomes higher. The similar phenomenon occurs for nuclei Z, but the relevant process is pair-production, $Z+\gamma_{2.7K}\to Z+e^{+}+e^{-}$ [22]. If a source is at the large distance this process causes the cutoff in the observed spectrum. Numerically the energy of this cutoff is usually given for a model where sources are distributed uniformly in extragalactic

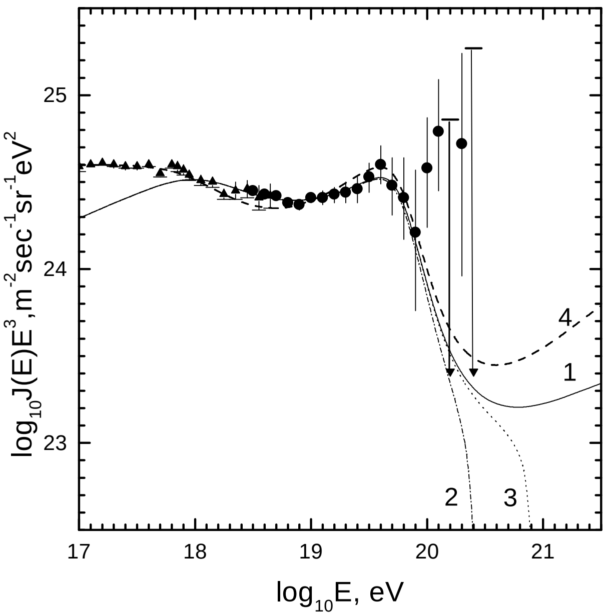

Figure 5: *Calculated diffuse spectra* [29] *for uniform distribution of UHECR sources in the Universe in case of cosmological evolution of the sources (curve 4) and without evolution (curves 1-3). The latter are given for different cutoff energies in the production spectra (*$E_{\max} = \infty,\ 3 \times 10^{20}$ *eV and* 1×10^{21} *eV, for curves 1, 2 and 3,respectively (see also* [42]*).*

space . In this case the cutoff starts at $E = 3 \cdot 10^{19}$ eV and the flux becomes half of its power-law extrapolation at $E_{1/2} = 5.3 \cdot 10^{19}$ eV (for these and other details of energy losses and absorption of different kind of primaries see Ref.[28]).

In Fig.5 the calculated spectra of protons are displayed for a model where the sources are distributed uniformly in the Universe with cosmological evolution of the sources (curve 4) and without it (curves 1 - 3). The evolutionary case is given for generation spectrum with spectral index $\gamma_g = 2.45$ and with evolution described as $(1 + z)^m$ with $m = 4$. The case without evolution, $m = 0$, is presented for power-law generation spectrum with index $\gamma_g = 2.7$ and with different cutoffs of generation spectra described by maximal energies $E_{max} = 3 \cdot 10^{20},\ 1 \cdot 10^{21}$, and ∞ [29]. The calculations are compared with recent AGASA data. The GZK cutoff in the calculated spectra is clearly seen, in contrast to the observed spectrum.

4.3 Extragalactic UHECR from Astrophysical Sources

An often asked question is: There could be a few extragalactic sources so close to us, that the observed spectrum does not suffer the GZK cutoff, what is the problem then?

The problem is the low energy part of the spectrum. It is formed by sources at large distances, and because of GZK cutoff these sources do not contribute to high energy part of the observed spectrum. One must specify his assumption about distribution of sources in the universe, and the uniform distribution is the simplest one.

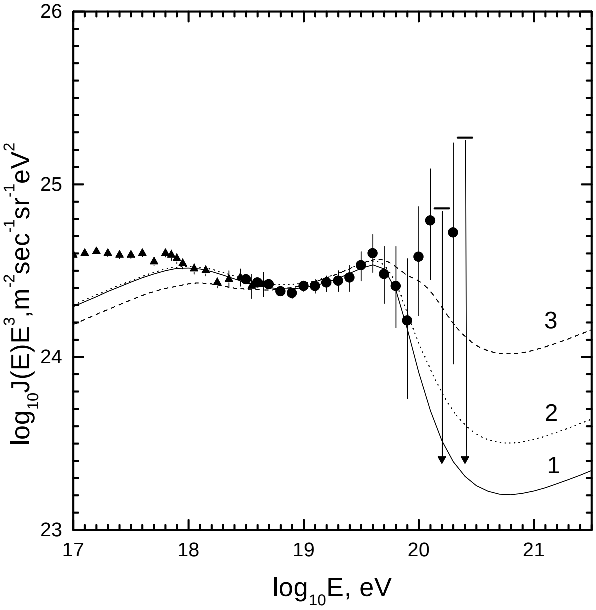

Figure 6: *Diffuse energy spectra with local overdensity of UHECR sources. Curves 1, 2 and 3 are given for uniform distribution of the sources, for overdensity* $n/n_0 = 2$*, and* $n/n_0 = 10$*, respectively. The linear size of overdensity region is 30 Mpc.*

GZK cutoff shifts to higher energies and becomes softer if population of sources has local (within 30 - 50 Mpc) overdensity. (for early calculations see [31)], described in [28)]). The count of galaxies show local overdensity with a factor ~ 2 within Local Supercluster. *Since overdensity is a gravitational phenomenon, one must expect the similar overdensity for all galactic-like sources of UHECR , i.e. ones with acceleration by stars, AGN and other intragalactic objects.* In Fig.6 the spectra of UHECR are shown for three cases: uniform distribution of the sources (curve 1), distribution with local overdensity $n/n_0 = 2$ within radius $R = 30$ kpc, and with local overdensity $n/n_0 = 10$ within radius $R = 30$ kpc. The calculations of spectra for observed distribution of galaxies were performed in Ref.[32)]. From Fig.6 one can see that to reconcile the data with observations, the overdensity of the sources must be considerably larger than that observed for the galaxies. This disfavours the idea. Another possibility to make GZK cutoff less pronounced is given by one-source model.

Let us assume that there are a few sources of UHECR in the Universe and by chance our Galaxy is located nearby one of them. In this case GZK cutoff is absent, but the price to be paid is anisotropy. In early work [33)] the Virgo cluster was considered as such source, and energy of cutoff and anisotropy was reconciled assuming the diffusive propagation of UHE particles. With new data on particle energies and anisotropy this model is excluded. An interesting revival of this idea was suggested in Ref.[34)]. Particles generated in M87 galaxy in Virgo cluster are propagating almost rectilinearly and are focusing to the Sun by galactic magnetic field. It provides arrival

to the Sun from different directions in agreement with absence of large anisotropy. Quasi-rectilinear propagation from Virgo provides absence of GZK cutoff.

A model of a nearby source with non-stationary diffusion was suggested in Ref.[35)]

4.4 Galactic Origin of UHECR

UHECR have no GZK cutoff in case of galactic origin. Starting with S.I.Syrovatsky [36)], the galactic origin of UHECR was advocated in many works (see for example [37,38,39)]). Observational data are in favour of pure proton composition at highest energies. As numerous simulations show, Galactic magnetic field cannot confine UHECR

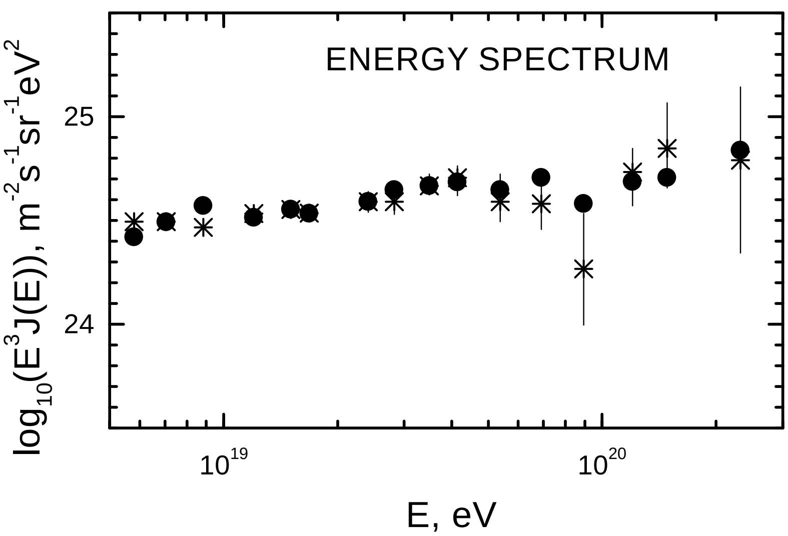

Figure 7: *Energy spectrum of UHE iron nuclei of galactic origin according to simulation* [40)] *for generation spectrum with* $\gamma_g = 2.3$*. Black circles show the calculated flux (ad hoc normalisation), stars – data of AGASA.*

in the Galaxy, if they are protons. A case when they are heaviest (iron) nuclei is more difficult for a conclusion. We shall present here results of the simulation of propagation of UHE particles in our Galaxy [40)] with conclusions concerning the iron nuclei as primaries.

The model is similar to one used in Ref.[41)]. The disc with UHECR sources is surrounded by extended spherical halo with radius which varies from 15 kpc to 30 kpc. Magnetic field in the disc has a spiral structure with a spiral arms and is given by complicated analytic expression, which fits observational data. The field is dominated by the azimuthal component. The thickness of magnetic disc is 0.4 kpc. The magnetic field in the halo is taken according to the theoretical model [42)] and is described by complicated analytic formulae (see also [41)]). The flux of UHE particle from given direction is calculated in the following way. Antiparticle with energy E is emitted in this direction and its trajectory if followed step by step until exit from the halo. A particle can cross the disc several times due to deflection by magnetic field in the halo.

The intensity in given direction is proportional to the total time, T_d, a particle spends in the disc. The energy spectrum is given by the product of generation spectrum $KE_g^{-\gamma_g}$ and $T_d(E)$. The calculated spectrum with $\gamma_g = 2.3$ is shown in Fig.7 in comparison with AGASA data. One can see excellent agreement.

However, the real problem is given by anisotropy. In Fig. 8 the disc anisotropy is calculated as the ratio of the flux from direction of the disc to the total flux. At energy $E \geq 4 \cdot 10^{19}$ eV the calculated anisotropy exceeds the observed value.

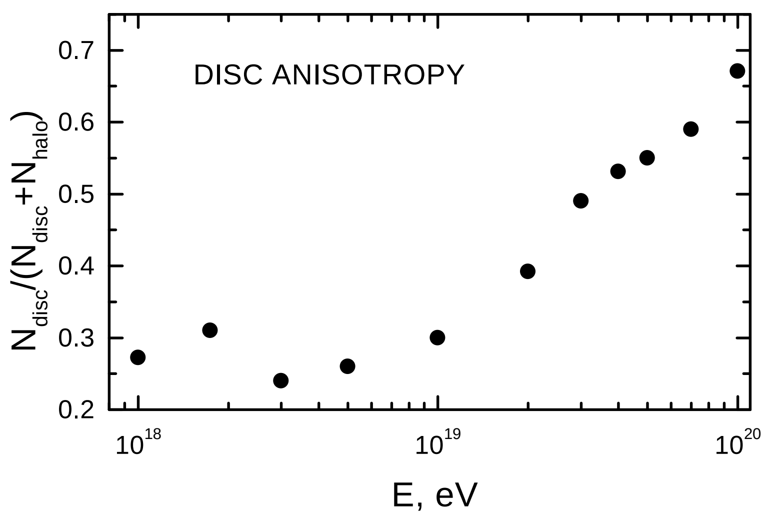

Figure 8: *Disc anisotropy of UHE iron nuclei according to simulation* [40]

4.5 New physics

Although is not yet excluded, the astrophysical solution to UHECR problem is strongly disfavoured. We shall shortly describe here the elementary-particle solutions not giving the references (for a review of elementary-particle solutions see [43])

- *Superheavy Dark Matter.* Long-lived Superheavy Dark Matter Particles are accumulated in galactic halos. These particles are naturally produced at post-inflationary epoch and can close the Universe or contribute some fraction to Cold Dark Matter. These particles can be long-lived, with lifetime exceeding the age of the Universe. Decays of these particles produce UHECR without GZK cutoff (most of UHE particles come from Galactic halo). The dominant component is photons.

- *Topological Defects* (TD). There are different mechanisms of production of UHE particles by TD. In some cases TD become unstable and decompose to constituent fields (superheavy Higgs and gauge bosons), which then decay to ordinary particles. This mechanism works for cusps and superconducting cosmic

strings. In case of monopoles and antimonopoles connected by strings, high energy particles are produced at annihilation of monopole-antimonopole pairs. The most promising candidates are necklaces and monopole-antimonopole pairs connected by string. UHECR from TD has spectrum with a soft GZK cutoff which does not contradict observations.

- *Resonant neutrinos.* Very high energy neutrinos are resonantly absorbed by target neutrinos comprising Hot Dark Matter (HDM): $\nu + \bar{\nu}_{HDM} \rightarrow Z^0 \rightarrow$ *hadrons*. In the case HDM neutrinos have locally enhanced density, the GZK cutoff is absent or softened. Very large flux of primary neutrinos with superhigh energies are needed for this hypothesis.

- *Light gluino.* Light gluinos can be effectively produced by TD or in pp-collisions in astrophysical sources. They weakly degrade in energy interacting with microwave radiation. The interaction of UHE light gluino with nucleons is similar to that of UHE proton. Light gluino is disfavoured by accelerator experiments.

- *Strongly interacting neutrino.* In extra-dimension theories, for example, neutrino can have large cross-section of scattering off the nucleon. In this case neutrino can be a carrier of UHE signal from remote astrophysical sources.

- *Lorentz Invariance breaking.* In this case for protons with energies 10^{20} eV and higher, the c.m. energy could be not enough for production of pions in collisions with microwave photons (see section 2).

5. Mystery of GRB engine

Gamma Ray Bursts (GRBs) strike our imagination. On one hand, the tremendous energy release up to 2×10^{54} ergs during a short time of order of a few seconds, within the volume of order of the moon, implies a catastrophic event in the Universe. On the other hand we observe them once a day. All observed characteristics of GRBs vary within very wide range, fluences – within $10^{-8} - 10^{-4}$erg/s, durations – from a few ms up to a few thousand of sec, energy release – from 10^{50} to 10^{54} ergs in case of isotropic radiation. It is very plausible that there are several types of GRBs of different origin. In particular, the short bursts, shorter than 1s, and long bursts form two distinctive groups of GRBs.

The mechanism of radiation in GRBs is well understood. The unknown compact GRB engine explosively produces a fireball expanding in the surrounded plasma. An important parameter which determines the hydrodynamic expansion is the inverse baryon content, η, of the initial fireball, which is given by relation $\eta = \mathcal{E}_{GRB}/M_b c^2$, where $\mathcal{E}_{GRB}$ is the total energy of GRB and M_b is a baryonic mass. Value of η gives Lorentz factor of a fireball at the stage of saturation, which follows acceleration stage of expansion.

Electrons, accelerated in the fireball by the multiple internal shocks and as well as by the external and reversed shocks, produce soft gamma-ray radiation by synchrotron mechanism. When the external shock starts decelerating, the synchrotron emission of electrons occurs in X-ray and optical range. This is so called afterglow radiation .

For most of GRBs the host galaxies are not found. It could be explained by large error box determined for GRBs and by weakness of host galaxies. Only in 1996 Beppo-SAX discovered the first host galaxy due to afterglow radiation. Since that time for more than 20 GRBs the host galaxies were reliably found. All galaxy-hosted GRBs have long durations and are located at large distances.

The Beppo-SAX discovery gave us a clear indication to the location of the sources: at least some of them (and maybe all) are the galactic objects. For astrophysical objects the greatest energy release is given by gravitational collapse. In principle, energy release at the collapse can reach 29% of the collapsed mass in case of a black hole with maximal rotation. It gives $\sim 1 \cdot 10^{54}$ erg for a collapse of 1 $M_\odot$ stellar core, but it is difficult to imagine that all this energy can be transferred to GRB.

Strong beaming can solve the energy problem and this beaming looks like an inevitable element of any realistic astrophysical model of GRB engine.

The moderate beaming is a common feature observed e.g. in AGNs and mini-quasars in our Galaxy, e.g. SS433, but it is hard to imagine a model of collapsar with beaming factor, e.g. $\sim 10^{-2} - 1-^{-3}$. As Blandford said[44]:
"Are GRBs beamed? ...
the argument that the bursts must be beamed, otherwise they would have energies in excess of stellar rest mass, reminds me of a similar argument in favor of them being local!"

Although general principles allow collapsars as GRB engines with required energy release up to $\mathcal{E}_{GRB} \sim\ 10^{54}$ erg, there are no models which practically realize this possibility. We shall describe shortly four recent collapsar models for GRB engines.

The most elaborated model is a binary neutron star merger NS-NS, or a similar binary system from neutron star and black hole, NS-BH. This was first suggested in ref.[45], for the recent calculations and references see [46]. Merging of two NSs , or NS and BH results in collapse with emission of neutrinos. The latter annihilate $\nu + \bar{\nu} \to e^+ + e^-$, producing relativistically expanding fireball. Numerical simulations [46] give the total energy of neutrinos in the burst $\sim 3 \times 10^{52}$ erg, but annihilation efficiency is very low (1-3%). Apart from small total energy $\mathcal{E}_{GRB} \sim 10^{51}$erg this model predicts very short burst duration $\tau \leq 0.1$ s, which corresponds to a small fraction of the observed GRBs.

The second model[47], "failed SN" starts with the collapse of single rotating Wolf-Rayet star. As the core of this star collapses, it accrets the gas from the mantle. Neutrinos interact with accretion disc, producing a fireball. The total energy transferred to fireball is estimated as $\mathcal{E}_{GRB} \sim 10^{51}$ erg. One cannot expect large beaming in this model. Duration of the bursts is rather short, less than 10 s. The model

predicts too large baryon contamination, in contradiction with hydrodynamic part of the model. This model is based on the estimates and should be called scenario.

The two models described above, use neutrino radiation which has low efficiency of conversion into fireball energy. An interesting collapse scenario (hypernova) without involving neutrinos was suggested in Ref.[48]. A massive black hole with mass $M_{bh} \sim 10M_\odot$ is produced in the end of evolution of single star. It has superstrong magnetic field $B \sim 10^{15}$ G and fast rotation corresponding to rotational energy $E_{rot} \sim 5 \times 10^{54}$ erg. Magnetic field by its pressure expels the outer shell. A small fraction of it moving in the region with decreasing density is accelerated to relativistic velocities by the Colgate mechanism. The hypernova scenario does not need narrow beaming and predicts large GRB duration. However, it predicts too large baryonic contamination. This scenario involves a possible sequence of physical phenomena taken with extreme values of parameters. It is hard to perform numerical calculations for such scenario.

The weakness of hypernova scenario (large baryon contamination) is evaded in Supranova scenario [49]. The massive neutron star is stabilised by rotation. The loss of angular momentum results in collapse like in hypernova scenario, and a fireball is produced by expanding magnetic field. In this scenario the baryon contamination is low, it is provided by swept up baryons from interstellar region.

In conclusion, the astrophysical models for GRB engine, which allow numerical calculations, predict too low energy release and need narrow beaming, which does not naturally exist in these models. In some scenarios, most notably hypernova, there could be a set of physical phenomena, which when taken with extreme parameters can provide the energy release and durations needed for explanation of observed GRBs. However, as it stands, these scenarios do not give numerical predictions and, strictly speaking, cannot be called models.

5.1 GRBs from superconducting strings

Can the problem of GRB engine with its tremendous energy release, probably beamed, be solved with a help of a new physics?

Such a solution, utilising the cusps of superconducting strings, was first suggested in Refs.[50] and recently revived in Ref.[51].

Cosmic strings are linear defects that could be formed at a symmetry breaking phase transition in the early universe [52]. In the space they exist in the form of endless strings and closed loops. Strings predicted in most grand unified models respond to external electromagnetic fields as thin superconducting wires [53]. As they move through cosmic magnetic fields, such strings develop electric currents. Oscillating loops of superconducting string emit short bursts of highly beamed electromagnetic radiation through small string segments, centered at peculiar points on a string, cusps, where velocity reaches speed of light [54,55].

The beam of low-frequency e-m radiation propagating in plasma produces a beam of accelerated particles. For an e-m wave in vacuum, a test particle would be accel-

erated to a very large Lorentz factor. But the maximum Lorentz factor of the *beam* is saturated at the value γ_b, when the energy of the beam reaches the energy of the original e-m pulse: $N_b m \gamma_b \sim \mathcal{E}_{em}$. This results in the Lorentz factor of the beam of order $10^2 - 10^4$ like in ordinary fireball. The beam of accelerated particles pushes the gas with the frozen magnetic field ahead of it, producing an external shock in surrounding plasma and a reverse shock in the beam material, as in the case of ordinary fireball. Therefore the hydrodynamic development of a fireball is essentially the same as in case of astrophysical GRB engine.

In contrast to astrophysical models, a cusp produces pulse of e-m radiation with energy and beaming fixed by parameters of cosmic strings and ambient gas. In fact, the cusp model is very rigid. In a simplified version [51] there is only one free parameter, the string scale of symmetry breaking $\eta \sim 10^{14}$ GeV, and two physical quantities which characterise gas in filaments and sheets, where most of GRBs are originated. Formally there are three such quantities: magnetic field, parametrised as $B = B_{-7} 10^{-7}$ G, redshift of its origin z_m and gas density n_g. But dependence on gas density is extremely weak. It influences only hydrodynamic flow through Lorentz factor of contact discontinuity surface , γ_{CD}, with $\gamma_{CD} \propto n_g^{-1/8}$.

The only genuine free parameter, η, or equivalently dimensionless parameter $\alpha = k_g G \eta^2$, where G is a gravitational constant and $k_g \sim 50$ is a numerical coefficient, determines the space properties of the loops: a typical length of a loop at epoch t, $l \sim \alpha t$ and the number density of loops

$$n_l(t) \sim \alpha^{-1} t^{-3}. \tag{10}$$

A string segment near the cusp moves with Lorentz factor γ and radiates e-m pulse within a cone with opening angle $\theta \sim 1/\gamma$. The energy radiated per unit of solid angle in the direction θ is given by [54]

$$d\mathcal{E}_{em}/d\Omega \sim k_{em} J_0^2 \alpha t/\theta^3, \tag{11}$$

where J_0 is initial current induced by external magnetic field in a loop.

The fluence, defined as the total energy per unit area of the detector, is

$$S \sim (1+z)(d\mathcal{E}_{em}/d\Omega) d_L^{-2}(z), \tag{12}$$

where $d_L(z) = 3t_0(1+z)^{1/2}[(1+z)^{1/2} - 1]$ is the luminosity distance.

After simple calculations [51] one obtains the GRB rate as a function of fluence. For relatively small fluences,

$$\dot{N}_{GRB}(>S) \approx 3 \cdot 10^2 S_{-8}^{-2/3} B_{-7}^{4/3}\ yr^{-1}, \tag{13}$$

while for large fluences $\dot{N}_{GRB}(>S) \propto S^{-3/2}$. Both absolute value of $\dot{N}_{GRB}(>S)$ and its dependence on S agree with observations. The duration of the cusp event as seen by a distant observer is [50]

$$\tau_c \sim (1+z)(\alpha t/2)\gamma^{-3} \sim (\alpha t_0/2)(1+z)^{-1/2}\theta^3. \tag{14}$$

The duration of the cusp event coincides with the duration of GRB, found as duration of fireball emission [51]. The duration of GRBs originating at redshift z and having fluence S can be readily calculated as

$$\tau_{GRB} \approx 200 \frac{\alpha_{-8}^4 B_{-7}^2}{S_{-8}} (1+z)^{-1} (\sqrt{1+z} - 1)^{-2} \ s \tag{15}$$

Analysis of Eq.(15) shows [51] that it correctly describes the range of observed GRB durations.

Therefore, simplified one-parameter cusp model describes correctly the total energies of GRBs (or fluences S), the GRB rates and their dependence on S, and GRB durations (absolute values and a range).

The signatures of this model are simultaneous powerful bursts of gravitational radiation [51,56] from a cusp and repeaters for GRBs of very short durations.

The cusp model meets basically one difficulty: it predicts too low GRB rate from galaxies. This discrepancy could be eliminated if the model strongly underestimates the capture rate of string loops by galaxies. For example, if $\alpha \gg k_g G\eta^2$, then the loops are non-relativistic and may be effectively captured by galaxies. Another possibility is that the cusp model could describes some subclass of the sources not associated with galaxies. Such a subclass could include the short-duration GRBs for which host galaxies are not found, or another subclass of no-host GRBs.

6. Conclusions

Astronomy and astrophysics were in the past and remain now a source of fundamental discoveries in physics. What phenomena can we suspect now as the challengers for such discoveries?

Most probably UHECR is a challenger number one. Presence of detected particles with energies above the GZK cutoff is reliably established. Astrophysical solution to UHECR problem is disfavoured, though not excluded. UHE heavy nuclei (iron) accelerated in our Galaxy, local (10 -30 Mpc) enhancement of UHECR sources and exotic one-source models remain disfavoured but not rigorously excluded possibilities. One might expect surprises here, but each of them will be a small revolution in a special field. There are many elementary-particle solutions to UHECR problem. All of them seem exotic to non-specialists, but eventually many of them not. For example, idea of UHECR from Superheavy DM is based only on known theoretical physics. Light gluino as a carrier of UHE signal is also based on reliable physics and may be saved by re-examination or re-interpretation of accelerator data. Only future experiments can can solve UHECR problem. The observations of UHECR in the southern hemisphere (the Auger detector), measurement of longitudinal profiles of EAS in the atmosphere (High-Res) and search for the particles with energies 1×10^{21} eV and higher (Auger,

Telescope Array and space detectors) may result in fundamental discovery in physics.

GRB engines with their tremendous energy output, most probably beamed, are new type of the sources even in case they are collapsars. Further observational evidences for their origin (more precise positions in the galaxies, no-host GRBs etc) will help to establish the nature of these objects, though they are well hidden in the debris of the bursts. Search for gravitational bursts and very short GRBs can bring evidence for non-astrophysical origin of at least part of GRBs.

I think TeV gamma-ray crisis will be peacefully solved by reconsideration of observed diffuse flux of IR radiation. It will result then in a better constraint on the Lorentz Invariance violation, not in its discovery.

7. Acknowledgements

It is my great pleasure to thank Milla Baldo Ceolin for organising most exciting conference and for magnificent hospitality.
This work has been performed as part of INTAS project No. 99-1065.

8. References

1) K.Hirata et al., Phys. Rev. Lett. **58** (1987) 1490,
R.M.Bionta et al., Phys. Rev. Lett. **58** (1987) 1494,
E.N.Alexeev et al., Sov. Astron. Lett. **14** (1988) 41.
2) V.S.Imshennik and D.K.Nadyozhin, Sov. Astr. Lett. **3** (1977) 353.
3) V.A.Kostelecki and S.Samuel, Phys. Rev. **D39** (1989) 683.
4) G.Dvali and M.Shifman, Phys. Rept. **320** (1999) 107.
5) J.Ellis, N.E.Mavromatos and D.V.Nanopolos, 4th International Symposium On Sources And Detection Of Dark Matter In The Universe (DM 2000), Marina del Rey, California, 20-23 Feb 2000, gr-qc/0005100.
6) Don Colladay and V.A.Kostelecky, Phys.Rev. **D55**, (1997) 6760.
7) S.Colemam and S.L. Glashow, Phys.Lett.**B405** (1997) 249;
S.Coleman and S.L. Glashow, Phys.Rev. **D59** (1999) 116008.
8) V.B.Berestetskii, E.M.Lifshitz and L.P.Pitaevskii, *Quantum Electrodynamics*, Pergamon Press, 1980.
9) K.Greisen, Phys.Rev.Lett., **16** (1966) 748;
G.T.Zatsepin and V.A.Kuzmin, Pisma Zh. Experim. Theor. Phys., **4** (1966) 114.
10) D.A.Kirzhnitz and V.A.Chechin, Pisma in ZhETP, **14** (1972) 261; D.A.Kirzhnitz and V.A.Chechin, Sov. Journal of Nucl. Phys., **15** (1972) 1051
11) L.Gonzales-Mestres, in *Proc. 25th Inter. Cosmic Ray Conf.*, Durban, **6** (1997)

109;
L.Gonzales-Mestres, in *Proc. 26th Inter. Cosmic Ray Conf.*, Salt Lake City, **1** (1999) 179.
12) S.L.Glashow, Nucl.Phys.B (Proc. Suppl.) **70** (1999) 180.
13) R.Aloisio, P.Blasi, P.L.Ghia and A.F.Grillo, Phys. Rev. **D62** (2000) 053010.
14) J.Ellis et al, Astrophys.J. **535** (2000) 139.
15) M.G.Hauser et al, Ap.J. **508** (1998) 25.
16) D.J.Fixsen et al, Ap.J. **508** (1998) 123
17) A.Biviano et al, astro-ph/9910314
18) M.A.Malkan and F.W.Stecker, astro-ph/0009500,
F.W.Stecker, IAU Symposium (eds M.Harwit and G.Hauser) **204** (2000), astro-ph/0010015
19) J.R.Primack, Astrop. Phys., **11** (1999) 93,
D.MacMinn and J.R.Primack, Sp.Sci.Rev. **75** (1996) 413.
20) R.J.Protheroe and N.Meyer, Phys. Lett. **B 493** (2000) 1.
21) J.Guy, C.Renault, F.A.Aharonian, M. Rivoal and J.-P.Tavernet, Astron.Astroph. **359** (2000)419.
22) V.S.Berezinsky,S.I.Grigorieva and G.T.Zatsepin, Proc. 14th Int.Cosm.Ray Conf.(Munick) **2** (1975) 711;
Izv.Acad.Nauk USSR (ser. phys) **40** (1976) 524.
23) V.S.Berezinsky, Soviet Phys.Nucl.Phys., **11** (1970) 399.
24) M.Nagano and A.A.Watson, Rev. of Mod. Phys. **72** (2000) 689.
25) A.M.Hillas et al, 12th Int. Cosm.Ray Conf. **3** (1971) 1001.
26) D.J.Bird et al, Ap.J. **424** (1994) 491.
27) S.Yoshida et al, Astrop. Phys. **3** (1995) 105.
28) V.S. Berezinskii, S.V.Bulanov, V.A.Dogiel, V.L.Ginzburg, and V.S.Ptuskin, *Astrophysics of Cosmic Rays*, North-Holland, 1990.
29) V.Berezinsky, A.Gazizov and S.Grigorieva, to be published in Proc. of ICRC 2001.
30) S.T.Scully and F.W.Stecker, astro-ph/0006112.
31) V.S.Berezinsky and S.I.Grigorieva, Proc. of 16th Int. Cosmic Ray Conf. (Kyoto), **2**, (1979) 81.
32) M.Blanton, P.Blasi and A.Olinto, Astrop. Phys. **15** (2001) 275.
33) J.Wdowczyk and A.Wolfendale, Nature **281** (1980) 356;
M.Giler,J.Wdowczyk and A.Wolfendale, J.Phys.G **6** (1980) 1561.
34) E-J Ahn, G.Medino-Tanco, P.L.Biermann and T.Stanev, Nucl.Phys. (Proc. Suppl.) **87** (2000) 417.
35) V.S.Berezinsky, S.I.Grigorieva and V.A.Dogiel, Astron.Astroph., **232** (1990) 582.
36) S.I.Syrovatsky, Comments Ap.Phys. **3** (1969) 155.
37) G.V.Kulikov, Yu.A.Fomin and G.B.Khristiansen, ZhETP Lett.,**11** (1969) 374.

38) M.Giller and M.Zielinska, Proc. 25th Int.Cosm.Ray.Conf. (Durban) **4** (1997) 469,
39) V.N.Zirakashvili et al, Astro. Lett. **24** (1998) 139.
40) V.Berezinsky, S,Grigorieva and M.Marchesini, im preparation.
41) V.S.Berezinsky et al, in *Astrophysical Aspects of Most Energetic Cosmic Rays*, ed. M.Nagano and F.Takahara, World Scientific, (1991) 134.
42) D.D.Sokoloff and A.M.Shukurov, Nature **347** (1990) 51.
43) V.Berezinsky, Nucl.Phys.B (Proc.Suppl) **87** (2000) 387.
44) R.D.Blandford, astro-ph/0001498.
45) D.Eichler, M.Livio, T.Piran and D.N.Schramm, Nature **340** (1989) 126.
46) H-Th.Janka et al, Ap.J. **527** (1999) L39; and astro-ph/0101357.
47) S.E.Woosley, Ap.J. **405** (1993) 273; Ap.J. **527** (1999)
48) B.Paczinski, Ap.J. **494** (1998) L45, astro-ph/9706232.
49) L.Stella and M.Vietri, Ap.J. **507** (1998) L45; Ap.J.**527** (1999) L43.
50) A.Babul, B.Paczynski and D.N.Spergel, Ap.J.Lett. **316**, L49 (1987), B.Paczynski, Ap.J. **335**, 525 (1988).
51) V.Berezinsky, B.Hnatyk and A.Vilenkin, astro-ph/0102366.
52) A. Vilenkin and E.P.S. Shellard, *Cosmic strings and other topological defects*, Cambridge University Press, Cambridge, 1994.
53) E. Witten, Nucl. Phys. **B249** (1985) 557.
54) A.Vilenkin and T.Vachaspati, Phys.Rev.Lett. **58** (1987) 1041.
55) D.N.Spergel, T.Piran and J.Goodman, Nucl.Phys. **B291**, (1987) 847.
56) T.Damour and A.Vilenkin, Phys.Rev.Lett. **85**, 3761 (2000)